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DSTO-TR-1126

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ABSTRACT

Halon 1301 has been the primary gaseous fire suppressant for total flooding applications on naval vessels since the mid 1960s. The speed and assurance of extinguishment has made it the popular choice, but other factors also contribute to its suitability as a fire suppressant. These factors include the ease of which the agent is dispersed, the minimal residue after release, its electrical non-conductivity and the minimal risk associated with short-term human exposure. Halons however, are ozone depleting substances and under the Montreal Protocol, production of these substances have been be subjected to a controlled phase-out.

A number of Halon 1301 alternatives have been assessed using a risk analysis approach. The analysis comprised identifying suppressant selection criteria and rating the suppressants against each criterion and each criterion was rated on the basis of its level of importance in different applications. Rating both suppressant behaviour and the importance of each of the criteria ensures that the end use is given due consideration in suppressant selection.

RELEASE LIMITATION

Approved for public release

DEPARTMENT OF DEFENCE
DEFENCE SCIENCE & TECHNOLOGY ORGANISATION
DSTO

Published by

DSTO Aeronautical and Maritime Research Laboratory
506 Lorimer St
Fishermans Bend, Victoria 3207 Australia

Telephone: (03) 9626 7000
Fax: (03) 9626 7999

AR-011-817
March 2001

APPROVED FOR PUBLIC RELEASE

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Executive Summary

Halon 1301 has been the primary total flooding gaseous fire suppressant for naval applications since the mid 1960s. The efficiency of Halon 1301 has made it the popular choice but other factors also contribute to its suitability as a fire suppressant. These factors include the ease with which the agent is dispersed, the absence of residue after release and extinguishment, its electrical non-conductivity and the minimal risks associated with short-term human exposure. This combination of properties has made Halon 1301 attractive for naval fire control applications where fire is a threat to personal safety and the security of major assets.

Halons however, are ozone-depleting substances and their release into the atmosphere has contributed to the reduction in the ozone layer. The phase-out of halons and other ozone depleting substances is the basis of the Montreal Protocol, an international agreement designed to eliminate these substances. As a signatory to the Montreal Protocol, the Commonwealth of Australia has an obligation to phase out ozone depleting substances and enforces that obligation through the *Ozone Protection Act 1989*. Defence has an essential use exemption under the act and Halon 1301 can be used by the Royal Australian Navy (RAN). Halon 1301 fire suppressant systems are currently installed on the Collins class submarines, the Anzac class and FFG-7 frigates, however it is RAN policy to comply with the act where possible, which is why a non-ozone depleting replacement is sought.

Halon 1301 alternatives are available for total flooding applications and a number of these have been assessed for suitability as replacements. A risk assessment method was used to compare the Halon 1301 alternatives in which the criteria for suppressant selection is identified and the suppressant behaviour rated for each of the criterion. Each of the criterion were also rated against the level of importance in different applications. Rating suppressant behaviour and the importance of each of the criterion ensures that the application is given due consideration in suppressant selection.

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Stephen Kennett graduated from the University of Melbourne with a B.Sc. (Hons) in 1976, an M.Sc. (Nuclear Physics) in 1978 and a Ph.D. (Nuclear Astrophysics) in 1981. He commenced with the Department of Defence, Materials Research Laboratory, now the Aeronautical and Maritime Research Laboratory, Defence Science and Technology Organisation (DSTO) in 1981 and has undertaken research in interaction of lasers with materials, atmospheric optical propagation and laser eye protection. Since 1989 he has lead a team undertaking research into the effects of fire on life safety and asset protection on RAN vessels.

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Contents

1. Introduction

Halon 1301 has been the primary total flooding gaseous fire suppressant agent for naval applications worldwide since the mid 1960's and is currently used by the Royal Australian Navy (RAN) on the Collins class submarines, the Anzac class frigates and FFG-7 frigates. It's effectiveness at low extinguishing concentrations and its low toxicity have made it the popular choice, but other factors have also contributed to its widespread use as a fire suppressant. These factors include: rapid agent dispersion, minimal residue after release and extinguishment, electrical non-conductivity and the lack of physical damage as a result of use that is associated with suppressants such as water. This combination of properties has made Halon 1301 attractive for fire control applications where fire is a threat to personnel and major assets.

Halon 1301 is a halocarbon, a substance that comprises carbon, hydrogen and one or more of the halogen elements: fluorine, bromine, chlorine or iodine. Halon 1301 is known to contribute to the reduction in the ozone layer [1], the upper atmosphere (stratosphere) layer of ozone that absorbs most of the harmful ultraviolet-B and ultraviolet-C radiation emanating from the sun. Australia is a signatory to the Montreal Protocol [2], and has an obligation to phase out such ozone depleting substances. The RAN continues to use Halon 1301 through an exemption within the Ozone Protection Act [3], the legal framework that is used to meet Australia's obligations within the Montreal Protocol. Exemptions are granted where it can be shown that a product is essential for Defence purposes and practical alternatives are not available. However, the RAN will comply with the act requiring an acceptable alternative to Halon 1301.

In this paper, a risk management approach is used to evaluate a number of Halon 1301 alternatives for use on RAN ships. This method involves the identification of criteria against which a suppressant can be assessed, and an assessment of each alternative against these criterion.

2. Fire Suppression Criteria for Halon 1301 Replacement for RAN Applications

Fire suppression agents must suppress a fire rapidly to minimise damage as a result of fire. However, this is not the only criterion by which suppression agents are evaluated. Thirteen criteria have been identified against which suppressants can be rated. Eight are common to those selected in the United States Naval Studies Board evaluation [4] of alternative agents to replace Halon suppressants. These criteria comprise:

- *Fire suppression effectiveness*

The fire suppression effectiveness of a total flooding agent measured by the extinguishment concentration for a standard heptane cup burner (See section 5.1)

- *Delivery rate to a protected volume*

The delivery rate of a suppressant to a protected volume; achieving the extinguishing concentration in the shortest time reduces the likelihood of fire damage and the possibility of agent breakdown.

- *Toxicology*

The toxicology of the fire suppressants and protocols for their use.

- *Contribution to ozone layer depletion*

The contribution to the depletion of the ozone layer as measured by the Ozone Depletion Potential (ODP).

- *Effect on climate*

The contribution to climatic temperature increases as measured by the Global Warming Potential (GWP).

- *Environmental impact of decomposition products*

The contribution, by decomposition products produced during extinguishment, to ozone depletion and/or global warming.

- *Stability during storage*

The ability of a suppressant to resist chemical change during storage, affecting the behaviour and efficiency of the suppressant.

- *Compatibility of suppressants with distribution hardware*

Suppressants that react with system hardware materials (metals, elastomers or lubricants) during storage may result in suppressant leakage over time.

- *Volumetric efficiency*

The volume of suppressant gas necessary to achieve the extinguishing concentration compared to the volume of Halon 1301.

- *Hardware and suppressant cost*

The cost of the suppressant distribution system and agent could be a factor in the selection of a suppressant.

- *Obscuration on release of the agent*

The reduction in visibility when released into occupied areas, obscuring exit paths and obstacles.

- *Hold time*

The time that a suppressant will maintain its concentration in a protected space before being depleted by gravity or dispersion into surrounding areas. Heavier than air gases will be affected most, particularly where small fires will not produce the turbulence and air currents associated with more intense fires that equalise distribution of the suppressant.

- *Residue*

The residue that remains after a suppressant release will require cleaning up, this can be of importance in cases of accidental release.

3. Fire Suppression Mechanisms

A simple aid in understanding fire behaviour is the *Fire Tetrahedron* [5], see Figure 1, the apices of the tetrahedron represent the four components necessary for combustion. The components are fuel, oxygen, heat and the chemical reactions necessary to consume the fuel. If any of these components are removed, the fire cannot be ignited or sustained. The components can be removed by either physical or chemical means.

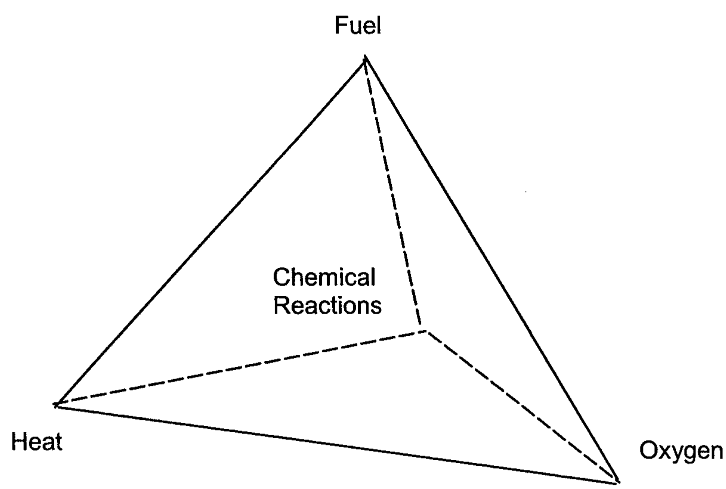

Figure 1. The Fire Tetrahedron

Physical fire suppression mechanisms remove heat, oxygen or fuel, and an example is the smothering of a fire, which separates the fuel and oxygen. Chemical fire suppression occurs

when a fire suppressant agent, or its decomposition products, modifies and disrupts the chemical reactions that constitute the combustion processes.

4. Fire Suppression Alternatives to Halon 1301 for RAN Applications

The Halon-like agents suppress fire by a combination of chemical and physical means and those examined in this work include;

FM-200,
Triodide,
PyroGen and
NAF-S-III.

Non-Halon-like alternatives rely only on physical mechanisms and those examined in this paper comprise the following;

Inergen,
Carbon dioxide (CO_2) and
Water mist.

A description of each suppressant agent; its chemical make-up and its suppression mechanism are given below.

4.1 FM-200

FM-200, also known as HFC-227ea, is manufactured by the Great Lakes Chemical Corporation. FM-200 is a hydroflourocarbon (HFC) with the chemical name heptafluoropropane and chemical formula CF_3-CFH-CF_3.

FM-200 suppresses fire by a combination of physical and chemical means. The primary extinguishing mechanism is physical, using a high heat conductivity to remove heat from the combustion zone. One of the secondary suppression mechanisms is chemical, where the heat of the fire causes the suppressant to breakdown and the breakdown products participate in the flame reactions, removing the chemical species necessary for flame propagation. The main breakdown product is hydrogen fluoride which is toxic.

FM-200, like Halon 1301 is stored as a liquid under pressure and the distribution hardware is similar to that of Halon 1301.

4.2 Triodide

Triodide is the trade name for triflouroiodomethane (CF_3I), an agent developed by Pacific Scientific as a total flooding agent. Triodide is chemically similar to Halon 1301, with an iodine atom substituting for the bromine atom in the Halon 1301 molecule.

Triodide extinguishes fires by chemical means. Iodine radicals are released as the product of thermal decomposition and consume the radicals produced during the combustion process which are necessary to maintain the flame.

Triodide is not recommended for occupied areas because of concerns over cardiac sensitivity from exposure at levels substantially below the extinguishing concentration.

4.3 PyroGen

PyroGen is a self-generating, total flooding aerosol suppression system produced by the PyroGen Corporation. The aerosol is generated in a non-pressurised container from a solid chemical by thermal or electrical means, it is generated and distributed rapidly, exhibiting gas-like dispersion qualities. The extinguishing action of PyroGen is achieved by altering the flame chemistry, heat absorption and dilution of the fuel and oxygen in the combustion zone by the aerosol cloud.

The aerosol consists of micron-sized potassium carbonate particles and the gases: carbon dioxide, nitrogen, water vapour, carbon monoxide and various nitrogen oxides. The potassium carbonate particles disassociate in the flame zone producing potassium radicals that interrupt the combustion reactions. PyroGen also suppresses fires by absorbing heat as a result of endothermic phases changes (solid to liquid to gas) and endothermic decomposition of the potassium carbonate particles.

PyroGen is unsuitable for fires involving the reactive metals: sodium, potassium, magnesium, titanium, zirconium, uranium and plutonium.

4.4 NAF-S-III

NAF-S-III is a hydrochlorofluorocarbon (HCFC) blend comprising 82% HCFC22, 9.5% HCFC124, 4.75% HCFC123 and 3.75% organic material and is manufactured by North American Fire Guardian Technology Inc. The organic material providing long term stability to the blend. NAF-S-III suppresses flames by chemical means, altering the flame chemistry through its decomposition products and has been developed as a direct replacement for Halon 1301 in total flooding systems.

As with other Halon-like suppressants, NAF-S-III produces hydrogen fluoride as one of its decomposition products.

NAF-S-III contains both ozone depleting and global warming substances, which may preclude its use as a total flooding agent however, the Montreal Protocol allows its use until 2030.

4.5 Inergen

Inergen is a mixture of inert gases comprising 52% nitrogen, 40% argon and 8% carbon dioxide, developed by the Wormald Group as a total flooding fire-suppressant agent. Inergen uses oxygen displacement to suppress fires, lowering the oxygen content to a level that will not support combustion, typically around 12%.

The Inergen gas mixture is stored under pressure as a gas, therefore the volume of Inergen required to reduce the oxygen content to 12% is substantial. The gas volume requirement necessitates large pressurised containers and consequently large storage facilities.

The carbon dioxide content in the Inergen mixture increases the human respiration rate allowing the body to absorb oxygen at oxygen levels as low as 12% [6]. The inclusion of carbon dioxide to the suppressant increases the safety of personnel in cases of accidental discharge Inergen is suitable for occupied areas, but will add to the level of carbon dioxide generated from fire by-products.

4.6 Carbon Dioxide (CO_2)

Carbon dioxide, CO_2, extinguishes fire by affecting two apices of the Fire Tetrahedron (Figure 1). The principal mechanism is the dilution of oxygen in the combustion zone, the secondary mechanism is heat absorption via a high heat capacity.

In fire suppressant systems, carbon dioxide is stored under pressure as a liquid, this method of storage is more efficient than the Inergen system, allowing a larger gaseous volume of suppressant to be available for fire control purposes.

Carbon dioxide is unsuitable for occupied areas.

4.7 Water Mist

Water mist fire suppression systems rely on a relatively fine (<200μm) water droplet spray to extinguish fires. The fine droplet size allows the spray to move around obstructions in a similar way to gaseous systems. The fire extinguishment mechanisms comprise flame cooling from water droplet evaporation, and oxygen depletion from the expansion of the steam generated by water evaporation.

Current technology water mist systems consist of either high pressure single fluid or low pressure twin fluid where the fluid is forced through specially designed nozzles to produce the required droplet sizes.

High-pressure systems can be wet or dry where wet systems are those that are pressurised up to the nozzle. High-pressure systems operate at pressures between 100 and 200 bar and consist of a water storage tank and high pressure pump to force the water through the nozzle, distribution piping, valving, nozzles and control system. Low-pressure systems do not generally require external pumps to produce water mist, compressed air and water are fed into a specially designed nozzle and the water atomised by the interaction of the two fluids. Low-pressure systems are dry; the distribution lines remaining unpressurised until activated.

Water mist has a major advantage when compared with conventional chemical suppressants. It is non-toxic and does not decompose into toxic by-products. In addition there are no adverse environmental concerns with its use.

Water mist systems are suitable for fuel fires, machinery and engine room spaces and computer and electronics applications [4], however it is unsuitable for fires involving reactive metals such as sodium and potassium.

5. Comparison with Fire Suppressant Criteria

The Halon 1301 alternatives have varying levels of performance for each of the criteria described in Section 2. To rank the alternatives, the performance against each of the criteria needs to be assessed.

5.1 Extinguishing Concentration

Gaseous suppressants are characterised by two extinguishing concentrations, the cup burner concentration and the minimum design concentration, both derived from a small laboratory device known as the cup burner. *n*-Heptane is used as a standard fuel and the cup burner value indicates the concentration of a substance required to extinguish a *n*-heptane flame. The minimum design concentration is deemed to be 1.2 times the cup burner value. This value allows for suppressant concentration variations due to incomplete mixing following a discharge. The extinguishing and minimum design concentrations of Halon 1301 and the replacement alternatives are listed in Table 1. For water mist systems, the volume of water necessary to lower flame temperatures to limiting levels for combustion are between 0.15–0.25 litres per cubic meter of space to be protected [4].

Table 1. Extinguishing and Minimum Design Concentrations of Halon 1301 and the alternatives.

Substance	Extinguishing Concentration Vol %	Minimum Design Concentration Vol %
Halon 1301	3.2[1]	5.0[1]
FM-200	6.6[1]	7.9[1]
Triodide	3.0[1]	3.6[1]
PyroGen	-	100 g/m^2
NAF-S-III	9.9[1]	12.0[1]
Inergen	29.1[1]	34.9[3]
Carbon dioxide	-	50.0[2]

1 UNEP Montreal Protocol, Halons Technical Committee Tech. Note 1, Revision 2, March 14, 1999
2 Fixed Fire Suppression Aerosol System for Industrial Applications, Design, Installation and Maintenance Manual, PyroGen, May 1999
3 Australian Standard AS 43314.2-1995, Gaseous fire extinguishing systems, Part 2: Inergen (IG-541) total flooding systems

5.2 Distribution

Systems employing FM-200 or NAF-S-III requires a greater gaseous volume than Halon 1301 to achieve the extinguishing concentration, but the suppressant discharge should occur over the same time. This increased volume of suppressant necessitates a change to the distribution system to facilitate discharge within the required time.

The amount of engineering to fit or retrofit a water mist system will depend on the type of system to be installed. A pump driven system would require a significant amount of engineering to adapt the distribution system, water storage and the high pressure pump units. The system would also require sufficient electrical power to drive the pumps. Gas pressurised systems would be less demanding with respect to system pressurisation.

Installation of a PyroGen system would result in minimal disruption when converting from Halon 1301. PyroGen gas generators are self-contained units requiring no distribution system. These generators can be installed or retrofitted with a minimum of re-engineering.

The water mist, Inergen and CO_2 systems have slow distribution speeds due to the volume requirement needed to reach their extinguishing concentrations compared to the Halon-like counterparts. The gas systems (CO_2 and Inergen) have a significantly greater extinguishing concentration than the Halon-like suppressants and take longer to achieve their respective extinguishing concentration.

Triodide, with a minimum design concentration less than Halon 1301, could be considered as a 'drop-in' replacement for Halon 1301. On discharge, the extinguishing concentration would be reached in a time similar to Halon 1301, adding to its attractiveness as a suppressant.

5.3 Human Safety

The risk of inhaling a quantity of a gaseous fire suppressants is extremely high in the event of a discharge into an occupied compartment. The risk to human safety depends on the suppressant's level of

- toxicity,
- cardiac sensitisation,
- oxygen depletion and
- toxic decomposition products.

Toxicity is determined from lethal dose experiments on rats, while cardiac sensitisation is determined from epinephrine-challenged beagle dogs.

Oxygen depletion is generally limited to the inert gas suppressants, the result of reducing the oxygen concentration to a level that will not support respiration.

On exposure to flame temperatures, Halon-like substances break down and produce products, predominantly hydrogen fluoride, which are harmful to human life.

5.3.1 Toxicity

The acute toxicity of a substance is the concentration of that substance that results in injury or death. This concentration is measured in two ways, the Approximate Lethal Concentration (ALC) and the LC_{50}. The ALC is the concentration at which lethal effects begin to occur and the LC_{50} is the concentration that kills 50% of test subjects exposed for a duration specified by a particular test protocol. Table 2 lists LC_{50} values for Halon 1301 and some of the total flooding system alternatives.

Table 2. LC_{50} values for Halon 1301 alternatives.

Substance	Test Subject	Duration	LC_{50} (Volume %)
Halon 1301	Rat	4 hours	80%[1]
FM-200	Rat	4 hours	80%[1]
Triodide	Rat	15 mins	27.4%[1]
NAF-S-III	Rat	4 hours	64%[1]

1 Triodide Gas Systems, Safety of Gaseous Extinguishing Products, http://www.orionsafety.com.au/product/triodide/paper1.html

The 8% CO_2 concentration in Inergen stimulates respiration and promotes the efficient use of oxygen at reduced levels. This behaviour makes Inergen suitable for occupied spaces. However, inert gas systems designed to reduce oxygen levels to below 10% should be restricted to unoccupied areas.

Carbon dioxide can result in unconsciousness and death within a few minutes from oxygen deficiency at concentrations of 10% CO_2 [7]. This concentration of CO_2 is substantially less than the minimum design concentration of 50% which makes carbon dioxide unsuitable for occupied areas. Physiological effects such as headache, nausea and physical weakening occur prior to the onset of unconsciousness, reducing the time available to make an escape. The Halon like alternatives; FM-200, Triodide and NAF-S-III each have LC_{50} levels that are greater than the extinguishing concentrations.

PyroGen has some toxicity concerns, primarily from the small concentrations of nitrogen oxides, carbon dioxide and carbon monoxide produced during the combustion reaction. The deep lung penetration of the insoluble sub-micron size particles can interfere with pulmonary function but the PyroGen particles are soluble and are unlikely to result in permanent lung cell damage [8].

Water mist systems using potable water do not present a toxicological or physiological hazard and are safe for use in occupied compartments [9].

5.3.2 Cardiac Sensitisation

Cardiac sensitisation describes the increase in sensitivity of the heart to epinephrine (adrenaline), a naturally occurring substance produced by the body under stress. If the heart is made more sensitive to epinephrine by exposure to a particular substance, it can be over-stimulated, resulting in irregular heartbeat and possibly heart attack.

Cardiac sensitisation is a function of the chemical concentration (of both the agent under test and the epinephrine) present in heart tissue which is assumed proportional to the concentration in the blood. Under steady state conditions, the concentration of the chemical in the blood approaches a constant value. Therefore the agent concentration in the bloodstream is a function of exposure concentration.

The procedure for evaluating cardiac sensitisation of the halogenated fire suppressants comprises a five-minute intravenous dosing of male beagle dogs with epinephrine to determine a baseline response. This is followed by inhalation of the suppressant for a further five minutes. The dogs are dosed again with epinephrine and monitored while exposed to the suppressant for a further 5 minutes. The cardiac activity in the animal is monitored for cardiac arrhythmia and the procedure is continued with increasing doses of agent until an effect occurs [10].

An electrocardiograph (ECG) monitors the responses, and an effect is considered to be the occurrence of five or more arrhythmias or ventricular fibrillations [4]. When the responses to a range of concentrations have been completed, the data are used to determine the concentration levels that define allowable exposure levels. These levels are called the *No Observed Adverse Effect Level (NOAEL)* and *the Lowest Observed Adverse Effect Level (LOAEL)*. The NOAEL is the highest concentration of a substance for which no adverse effect occurred and the LOAEL is the lowest concentration at which an adverse effect occurred.

The NOAEL is a protective level for human exposure and the design concentration of the suppressant must be less than the NOAEL concentration for occupied areas.

Studies have shown that the cardiac sensitisation levels in epinephrine challenged dogs may be a function of the dose of epinephrine as cardiac effects were not observed when epinephrine was not administered [11]. The release of epinephrine at the typical epinephrine dose in dog studies is about 10 times the release rate in humans under stress [12] and the cardiac sensitisation results from epinephrine challenged dogs may overestimate the responses in humans.

The NOAEL and LOAEL concentrations of Halon 1301 and its alternatives are listed in Table 3.

Table 3. NOAEL and LOAEL concentrations of Halon 1301 and the Halon replacement alternatives.

Substance	NOAEL % V/V	LOAEL % V/V
Halon 1301	5[1]	7.5[1]
FM-200	9.0[2]	10.5[2]
Triodide	0.2[2]	0.4[2]
NAF-S-III	10.0[2]	>10.0[2]
Inergen	43.0[2]+	52.0[2]++
Water mist	Not applicable	Not applicable

1 UNEP Montreal Protocol, Halons Technical Committee Tech. Note 1, Revision 2, March 14, 1999
2 Environmental project No. 312, 1995, Going towards Natural Fire Extinguishants, Ministry of Environment and Energy, Denmark, http:/www.mst.dk/pubs/no312/contents.htm
+ No effect level (NEL) ++ Low effect level (LEL) Based on physiological effects in humans in hypoxic atmospheres

The NEL and LEL are the NOAEL and LOAEL equivalents for Inergen and these values correspond to 12% residual oxygen for the NEL and 10% residual oxygen for the LEL [10]. The concern from exposure to inert gas suppressants is asphyxia due to oxygen deprivation and not cardiac sensitisation.

5.3.2.1 FM-200

The minimum design concentration for FM-200 is 8% for *n*-heptane fires, a concentration only marginally less than the NOAEL of 9%. However, variations in concentration in enclosed spaces due to poor mixing behaviour could raise the concentration to a level above the NOAEL.

5.3.2.2 Triodide

Triodide has a NOAEL of 0.2% which is substantially less than the design concentration of 3.6%. The data suggest that cardiac sensitisation may occur on exposure to Triodide at the minimum design concentration.

5.3.2.3 PyroGen

The products of a PyroGen discharge comprise solid potassium carbonate particles, carbon monoxide, carbon dioxide and oxides of nitrogen. The effects of exposure to this chemical combination will be dependent on the extinguishing concentration and the duration. Exposure to a standard extinguishing concentration of 100 g/m^3 in a sealed enclosure for up to 5 minutes may result in moderate irritation of the upper respiratory tract and the eyes. Exposure for up to 15 minutes may cause headache, nausea and shortness of breath and possibly some delayed reactions. Exposure over 15 minutes may result in unconsciousness or death [8].

The physiological responses to a PyroGen discharge are based on the toxin concentration levels generated from a standard PyroGen discharge and the physiological effect these toxins may have on humans.

5.3.2.4 NAF-S-III

The minimum design concentration of 12% for NAF-S-III exceeds the NOAEL of 10% and may result in cardiac sensitisation.

5.3.2.5 Inergen

The 1996 NFPA 2001 Standard [13] uses a No Effect Level (NEL) and a Low Effect Level (LEL) for Inergen instead of the NOAEL and LOAEL values. Inergen has an NEL of 43% (for 12% oxygen) and an LEL of 52% (for 10% oxygen). Safety decrees that design concentrations only up to the NEL be used for occupied spaces.

5.3.3 Decomposition Products

A major heath issue associated with Halon 1301 and Halocarbon substances are the by-products that result from decomposition at elevated temperatures. The principal decomposition product of halocarbon suppressants that affects human safety is hydrogen fluoride and the level produced is a function of the fire size and the time taken for the suppressant to reach the extinguishing concentration. Smaller, less energetic fires and rapid responses to fires result in reduced decomposition product concentrations. Suppressants that extinguish primarily by physical means, eg. cooling effect, produce greater concentrations of decomposition products than those that extinguish by chemical means. For total flooding systems, the volume of the protected space will also affect the amount of decomposition product produced; a small fire-energy to room size ratio will result in lower decomposition product concentrations, but external ventilation to the fire space will increase the

suppressant breakdown rate. Ventilation provides more oxygen, resulting in a more intense fire and an increased concentration of breakdown product.

From toxicity studies on rats, the LC_{50} value for hydrogen fluoride (HF) is 0.12% or 1,200 parts per million (ppm) for a one-hour exposure [14]. HF may also result in equipment damage in the presence of water. However short term failures (up to 90 days) of electronic equipment are unlikely for exposure to HF concentrations of 1,000 ppm for up to 30 minutes [15].

The Loss Prevention Council [16] have reported results of HF production in thermal decomposition studies. Data from these studies are presented in Table 4.

Table 4. Maximum HF concentrations for halogen type extinguishents.

SUBSTANCE	CONCENTRATION (%)	EXTINGUISHMENT TIME (SEC)	MAX HF CONCENTRATION (PPM)
Halton 1301 [16]	5.0	8.0	107
FM-200 [16]	7.0	Did not extinguish	8459
[16]	7.0	Did not extinguish	10234
[16]	7.0	15	1073
[16]	8.6	7.0	674
NAF-S-III [16]	12.0	8.0	1127

At the minimum design concentrations, Halon 1301 and Triodide produce the least amount of HF of the Halon-like alternatives [14].

The HF produced by NAF-S-III (Table 4) is approximately 1200ppm, comparable with LC_{50}. Results from Beck *et al* [17] show that for a 12% extinguishing concentration, the HF produced from large fire tests varied between 1000 and 9000 ppm (lethal levels).

FM-200 produced varying levels of HF, depending on the suppressant concentration and the fire type. FM-200 fuel fires (*n*-heptane) may not be extinguished at the lower concentration levels of 7%, resulting in HF in excess of the LC_{50} level. Beck *et al* [17] report HF concentrations of between 1500 and 5000 ppm which are above the LC_{50} for HF, for FM-200 discharges at extinguishing concentrations between 7.7 to 9%.

5.3.4 Oxygen Depletion

Human exposure to low oxygen concentrations can result in a loss of consciousness, brain damage and ultimately death, and the effect is more rapid as the oxygen concentration decreases or the exposure duration increases.

Oxygen depletion methods of extinguishment are specific to inert gas suppressant systems. The atmospheric oxygen concentration of air is 21% and inerting gas systems reduce this level to near 12% to suppress combustion. In any compartment a large fire will rapidly consume the available oxygen and an inert gas system will in this case lower the partial pressure of oxygen well below 12%.

With CO_2 systems, the concentration of suppressant required to reduce the oxygen concentration to 10% is approximately 50% by volume of CO_2. This concentration is significantly greater than the 10% CO_2 concentration that will probably result in death confirming its unsuitability for occupied spaces.

For an accidental release, the Inergen gas mixture allows respiration at 12% oxygen, which equates to 43% suppressant, the No Effect Level. However, in the presence of a large fire with the resultant low oxygen levels, Inergen gas could expose individuals to significant oxygen depletion.

5.4 Ozone Depleting Potential (ODP)

The ODP of a particular substance is a measure of the damage that substance can cause to the ozone layer and is a function of the chemical behaviour and stability in the upper atmosphere. The ODP is based on assigning a particular chlorofluorocarbon, CFC-11, a value of 1 and assigning other ozone depleting substances a relative number. Halon 1301 depletes ozone at a rate 10 times that of CFC-11 and is assigned an ozone depleting potential of 10. A list of the ODPs of Halon 1301 and the Halon replacements is shown in Table 5.

Table 5. Ozone Depleting potential of Halon 1301 and Halon replacements

Substance	Ozone Depleting potential
Halon 1301	10.0[1]
FM-200	0.0[2]
Triodide	0.008[2]
PyroGen	0.0[2]
NAF-S-III	0.05[2]
Inergen	0.0[2]
Carbon dioxide	0.0[2]
Water mist	0.0

1 UNEP Montreal Protocol, Halons Technical Committee Tech. Note 1, Revision 2, March 14, 1999
2 Environmental project No. 312, 1995, Going towards Natural Fire Extinguishants, Ministry of Environment and Energy, Denmark, http://www.mst.dk/pubs/no312/contents.htm

Ozone depletion is primarily controlled by chemistry, which is the reason that not all ozone-depleting substances have the same ozone depleting potential. CFCs fully substituted with halogen elements have high stability, allowing them to reach the upper atmosphere without breaking down. These substances are capable of reacting with and depleting ozone over long periods and as such, have a high ODP. Partially substituted CFCs, substances that contain hydrogen as well as halogens, begin to break down in the lower atmosphere and only a percentage will rise into the upper atmosphere where they can react with and destroy ozone.

5.5 Global Warming Potential (GWP)

The GWP is a measure of the effect that a substance has on tropospheric temperatures (up to 16 km from the earth's surface). The value is the ratio of the warming caused by a substance to the warming caused by a similar mass of carbon dioxide, where the GWP of CO_2 is defined as 1. Substances with a long atmospheric lifetime will have a more pronounced effect on global warming and ozone depletion than substances with a short lifetime. The global warming potential of Halon 1301 and the Halon 1301 replacements are listed in Table 6. It should be noted that non-ozone-depleting substances might still have a global warming potential.

Table 6. Global warming potential of Halon 1301 and Halon replacements.

Substance	Global Warming Potential
Halon 1301	6,900[1]
FM-200	3,300[2]
Triodide	0.0[2]
PyroGen	0.0[3]
NAF-S-III	1,600[2]
Inergen	0.0[2]
Carbon dioxide (100%)	1.0[2]
Water mist	0.0

1 UNEP Montreal Protocol, Halons Technical Committee Tech. Note 1, Revision 2, March 14, 1999
2 Environmental project No. 312, 1995, Going towards Natural Fire Extinguishants, Ministry of Environment and Energy, Denmark, http:/www.mst.dk/pubs/no312/contents.htm
3 Fixed Fire Suppression Aerosol System for Industrial Applications, Design, Installation and Maintenance Manual, PyroGen, May 1999

5.6 Environmental Consequences of Decomposition Products

The decomposition products from halon-like suppressants include HF (hydrogen fluoride), HCl (hydrogen chloride), HBr (hydrogen bromide) and HI (hydrogen iodide). These substances migrate up through the atmosphere but are soluble in water and removed by rain before they reach the ozone layer. The acid deposited by the rainwater is unlikely to be a concern because of the relatively small amount of decomposition product released into the atmosphere from fire suppression systems.

Inergen, CO_2 and water mist do not produce decomposition products.

5.7 Storage Stability

Temperature effects may cause deterioration in suppression agents. Triodide degrades at 100°C and degradation accelerates as the temperature increases [18]. The presence of moisture and/or copper also accelerates the rate at which Triodide degrades. Ambient temperatures on board naval vessels should not have an effect on the long-term storage stability of Triodide.

Halon 1301 and FM-200 have been found to be stable up to 150°C in the presence of a number of metallic materials used in storage facilities [19].

5.8 Compatibility with Distribution Hardware

The Halon-like suppressants tend to be chemically stable but can affect the organic materials used for seals and lubricants within the distribution hardware [4]. The important factor is the contact time of the suppressant and the hardware and this will depend on how the system is configured. If the distribution pipe-work is charged with suppressant then there will be a

greater probability of system degradation than if the storage bottles are discharged only when required. The contact time for the suppressant and organic materials will be minimised and the life of the distribution hardware extended.

Water mist systems require compatible materials to prevent corrosion of system components.

PyroGen is a self-contained fire suppressant system. The aerosol is non-conductive and non-corrosive. However, the aerosol generators have a prescribed shelf life and should be replaced at the prescribed intervals to maintain the system integrity.

Acidic decomposition products from the breakdown of Halon-like substances may have a deleterious effect on distribution hardware as a result of acid attack. However, ensuring the fire is extinguished in the shortest possible time will reduce the effect.

5.9 Volumetric Efficiency

The volumetric efficiency describes the volume of a suppressant necessary to achieve the extinguishing concentration when compared with Halon 1301. Of all of the alternatives examined, only Triodide has a greater volumetric efficiency (Table 7). High volume systems such as Inergen and CO_2 may be inappropriate for maritime applications where space may be at a premium.

Water mist systems atomise water either by pumping the water (at high pressure) through small orifices producing a fine spray, or by applying a high velocity gas stream (air or nitrogen) to a low-pressure water stream at a nozzle. The gas-pressurised systems take up significantly less space than the pump system and their distribution configuration are comparable to the Halon systems.

The PyroGen system is volumetrically very efficient, requiring only the self-generating suppressant canisters to provide fire protection.

Table 7. Storage volume requirements for Halon 1301 and Halon replacements.

Substance	Storage volume requirement relative to 1301
Halon 1301	1
FM-200	1.7[1]
Triodide	0.6[1]
NAF-S-III	1.4[1]
Inergen	10[1]
Carbon dioxide	4[1]

1 UNEP Montreal Protocol, Halons Technical Committee Tech. Note 1, Revision 2, March 14, 1999

5.10 Hardware and Suppressant Costs

Triodide and NAF-S-III can be considered as drop-in replacements for Halon 1301 because of the similar volume requirements for fire suppression and converting to these systems would not require extensive re-engineering. However, NAF-S-III requires 1.4 times the gas volume of Halon 1301 to reach its design concentration, and may require some modification to the distribution system to achieve its design concentration in the same time as Halon 1301.

Water mist systems require sufficient space for water storage, a pressurised gas cylinder or cylinder bank and high-pressure pumps. Substantial piping modifications would be necessary for distribution, together with sufficient electrical power to drive the pumps.

As a self-generating aerosol, the PyroGen system does not require space-consuming pressurised storage cylinders or pipework to deliver the suppressant. Depleted PyroGen canisters can be replaced without the need to return to base, resulting in a minimum of down time.

FM-200 systems would require modification to the storage and distribution network due to the greater volume of FM-200 required to achieve the design concentration when compared with Halon 1301.

High suppression agent costs can be offset by a reduced amount of suppressant needed to achieve the minimum design concentration. These costs are listed in Table 8, as are piping installation costs for each of the systems. The costs are 1995 figures (with the exception of PyroGen) and although dated, can be used to compare the costs associated with different systems.

The costs in Table 8 do not represent total installation costs; control systems, pressure containers and water mist requirements other than the piping network are not included.

Table 8. Replacement system installation and agent unit costs.

AGENT	AGENT COST US$/KG*	AGENT TO ACHIEVE MINIMUM DESIGN CONCENTRATION (20°C)	AGENT COST TO ACHIEVE MINIMUM DESIGN CONCENTRATION*	INSTALLATION COST $ PER CUBIC METRE*
FM-200	40 (1)	0.63kg/metre^3 (2)	$25/metre^3	120 (1)
Triodide	150 (1)	0.30 kg/metre^3 (2)	$45/metre^3	**
PyroGen	70 (3)	0.1 kg/metre^3 (2)	$7/metre^3	***
NAF-S-III	40 (1)	0.53 kg/cub metre^2	$21/metre^3	**
Inergen	7/metre^3 (1)	0.46 metre^2/metre^3 (2)	$3/metre^3	100 (1)
CO_2	2 (1)	1.6kg/metre^3 (2)	$5/metre^3	75 (1)
Water mist	-	-	-	120 (1)

1 Environmental Project No. 312, 1995, Going towards natural fire extinguishants, Ministry of Environment and Energy, Denmark. http://www.mst.dk/pubs/no312/contents.htm

2 Australian Standard AS 43314.2, Gaseous fire extinguishing systems

3 Personal Communication from AES International, NSW, Australia

*installation and agent costs are quoted in US dollars

**developed as a replacement for Halon 1301 and can be used in existing Halon 1301 systems with minor modifications.

***Installation comprises the wiring of the agent canisters to sensors. Depleted canisters can be replaced without the need to return to base, resulting in minimum down time.

5.11 Obscuration

Inergen is the only suppressant examined that does not fog to a substantial degree during a cold discharge. The CO_2 and the halocarbon suppressants discharge at temperatures below the dew point of water vapour causing fogging. Results presented by the Loss Prevention Council [16] show that obscuration from FM-200 and NAF-S-III discharges can take in excess of 250 seconds to lift.

Water mist systems fog because they produce water droplets, but the level of obscuration will depend on the droplet size. Smaller droplets result in higher levels of obscuration.

PyroGen releases will result in some obscuration due to the potassium carbonate particulate released.

5.12 Hold Time

Each of the Halon-like suppressants and the inerting gases are heavier than air and will have relatively short hold times because of the influence of gravity. Water mist comprises heavier than air water particles, but their hold time will be dependent on the droplet size; larger particles having a shorter hold time. PyroGen is composed of hot particles and gases and the heat generated by the system will extend the hold time. However, the particles and gases

will descend as the temperature falls. The behaviour of heavier than air suppressants can affect the suppressant effectiveness when fires are not near floor level.

5.13 Residue

The residue remaining after an accidental release will require cleaning up and the ease of clean up operations is important. However, after a fire, the amount of agent residue produced will be insignificant compared to the fire damage.

The gaseous suppressants are clean agents and leave no residue, but PyroGen and water mist will. PyroGen will produce a particulate residue that can be wiped or vacuumed. Water mist will need to be soaked up and equipment dried.

5.14 System Mass

Fire suppressant system mass can have a bearing on the suitability of systems for particular applications. Heavy systems are unlikely to be a major problem in maritime applications. However the suppressant system mass may be critical in aircraft systems.

6. Risk Assessment

Halon 1301 is currently used on some Australian naval vessels and will continue to be used until an acceptable alternative is identified from the range of suppressants available.

The criteria for selection of a total flooding suppressant agent have been described in this paper and the performance of the suppressants is assessed by rating the criteria. For each of the suppressants, the criteria are rated as good, fair or poor and a numerical value of 4, 2 and 0 attributed to these ratings. The ratings are presented in tabular form in Table 9 together with a cumulative rating for each of the agents, obtained by summing the scores over all criteria. Each criterion is assumed to be of equal importance and is therefore given equal weighting.

Table 9 . Rating of suppressants for each of the selection criteria for Halon 1301 and the Halon alternatives.

CRITERIA	SUPPRESSANT							
	Halon 1301	FM-200	Triodide	PyroGen	NAF-S-III	Inergen	CO_2	Water Mist
Extinguishing Concentration								
Distribution speed								
Hold time								
Suppressant toxicity I (Lethality - LC_{50})								
Suppressant toxicity II (Affect - NOAEL)								
Post exitinguishment toxicity								
ODP								
GWP								
Environ. consequences of decomp products								
Storage stability								
Cost of Agent								
Cost of Hardware								
Hardware compatibility								
Volumetric efficiency								
Residue								
Obscuration								
Mass								
Rating	48	44	50	50	42	48	32	48

Legend : Good (4) Fair (2) Poor (0)

The cumulative scores for each of the suppressants over all of the criteria indicate that Triodide, PyroGen, Inergen and water mist would be the preferred alternatives to Halon 1301. Each of these suppressants achieves a rating similar or better than Halon 1301.

The assessment, however, has not assigned any weighting to the individual criteria, a factor that takes into account the importance of each of the criterion for a particular application. The cumulative scores for each of the suppressants show some anomalies. Triodide scores

equal highest but its NOAEL is significantly below the design concentration affecting its suitability for use in occupied spaces.

The selection of a fire suppressant also requires the end-use and the principal fire threat to be identified. This procedure allows criteria relevant to the application to be given further consideration. A number of applications and common fire threats are listed in Table 10. The first four are typical naval applications for fire suppression systems while the remaining applications are included to show that the assessment procedure can be used for non-naval applications.

Table 10. Applications and fire threats.

APPLICATION	THREAT
1. Ship machinery room (occupied space)	Fuel spray
2. Encl'd machinery space	Fuel spray
3. Computer room (occupied space)	Electrical fire
4. Enclosed cabinet space	Electrical fire
5. Aircraft engine bay	Fuel spray
6. Aircraft cabin (occupied space)	Class A fire (wood, paper, plastics)
7. Land vehicle cabin (occupied space)	Ordnance Explosion

Ratings have been assigned to each criterion based on the authors' interpretation of the importance of each criterion for each application. Each criterion is rated 0, 2, 4 and 6 in order of increasing importance in relation to the application. The ratings of the criteria for the applications listed in Table 10 are shown in Table 11.

Table 11. Ratings for criteria for each of the applications.

CRITERIA	SHIP MACH'Y ROOM	ENCLOSED MACH'Y SPACE	COMPUTER ROOM	ENCLOSED COMPUTER CABINET	AIRCRAFTT CABIN	AIRCRAFT ENGINE BAY	LAND VEHICLE CABIN
Ext. Conc.	0	0	0	0	0	6	0
Dist. Speed	4	4	6	6	6	6	6
Hold Time	6	6	6	6	6	0	4
LC_{50}	6	2	6	2	6	2	6
NOAEL	4	2	4	2	4	2	4
Post extinguishment toxicity	6	2	6	2	6	0	6
ODP	6	6	6	6	6	6	6
GWP	2	2	2	2	2	2	2
Environmental consequences of decomposition	2	2	2	2	2	2	2
Storage stability	4	4	4	4	4	4	4
Agent cost	2	2	2	2	2	2	2
Hardware cost	2	2	2	2	2	2	2
Hardware compatibility	2	2	2	2	2	2	2
Volumetric efficiency	4	4	2	2	6	6	6
Residue	0	0	4	4	2	0	0
Obscuration	6	2	4	2	6	0	6
System mass	2	2	2	4	6	6	6

The measure of a suppressant's capability will be a function of the performance rating given to each of suppressant for each of the criteria (Table 9) and the importance attributed to each of the criteria (Table 11) for each particular application. The product of these two values will produce a weighted rating for each suppressant for each of the applications listed in Table 10 and these are presented in Tables 12 to 18.

The highest cumulative score in each table indicates the most suitable suppressant for that particular application. The cumulative scores for each suppressant are also presented as a percentage of the maximum score obtainable for each suppressant. The percentage of the maximum score defines how far removed from ideal each of the suppressants is. The cumulative score for each suppressant for each application are also presented as histograms in figures 2 to 7.

Table 12. Weighted criteria ratings for Ship Machinery Room (fuel spray fire).

CRITERIA	HALON 1301	FM-200	TRIODIDE	PYROGEN	NAF-S-III	INERGEN	CO_2	WATER MIST
Ext. Conc.	0	0	0	0	0	0	0	0
Dist. Speed	16	16	16	8	16	0	0	8
Hold Time	12	12	12	12	12	12	12	12
LC_{50}	24	24	24	12	24	24	0	24
NOAEL	16	16	0	8	16	16	0	16
Post exting. toxicity	24	0	24	12	0	24	0	24
ODP	0	24	24	24	12	24	24	24
GWP	0	0	8	8	0	8	8	8
Environ. consequences of decomp	8	8	8	8	8	8	8	8
Storage stability	16	16	16	16	8	16	16	16
Agent cost	4	4	0	8	4	8	8	8
Hardware cost	4	4	4	8	4	4	4	4
Hardware compat.	8	8	8	8	8	8	8	4
Volumetric Efficiency	16	8	16	16	8	0	0	16
Residue	0	0	0	0	0	0	0	0
Obscuration	0	0	0	0	0	24	0	0
System mass	4	4	4	8	4	0	0	4
Total	152	144	164	156	124	176	88	176
Ideal total	232							
% of ideal	66	62	71	67	53	76	38	76

Inergen, water mist and Triodide rate highest for the ship machinery room application. However this is an occupied space and the NOAEL for Triodide is below the extinguishing concentration, raising doubts about its suitability. The use of the Inergen system for this type of application would most likely prove unacceptable due to the volume of gas required to obtain the design concentration.

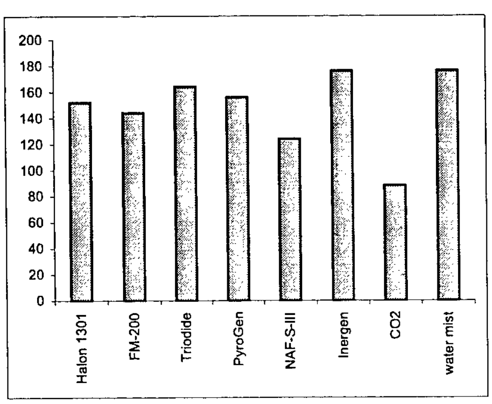

Figure 2. The cumulative citeria rating plotted for each suppressant for the Ship Machinery Room(fuel spray fire).

Table 13. Weighted criteria ratings for an Enclosed Machinery Space (fuel spray fire).

CRITERIA	HALON 1301	FM-200	TRIODIDE	PYROGEN	NAF-S-III	INERGEN	CO_2	WATER MIST
Ext. Conc.	0	0	0	0	0	0	0	0
Dist. Speed	16	16	16	8	16	0	0	8
Hold Time	12	12	12	12	12	12	12	12
LC_{50}	8	8	8	4	8	8	0	8
NOAEL	8	8	0	4	8	8	0	8
Post extinguishment toxicity	8	0	8	4	0	8	0	8
ODP	0	24	24	24	12	24	24	24
GWP	0	0	8	8	0	8	8	8
Environmental consequences of decomposition	8	8	8	8	8	8	8	8
Storage stability	16	16	16	16	8	16	16	16
Agent cost	4	4	0	8	4	8	8	8
Hardware cost	4	4	4	8	4	4	4	4
Hardware compatibility	8	8	8	8	8	8	8	4
Volumetric efficiency	16	8	16	16	8	0	0	16
Residue	0	0	0	0	0	0	0	0
Obscuration	0	0	0	0	0	8	0	0
System mass	4	4	4	8	4	0	0	4
Total	112	120	132	136	100	120	88	128
Ideal total	176							
% of ideal	64	68	75	77	57	68	50	73

For unoccupied areas such as enclosed machinery spaces, the preferred suppressants based on the cumulative scores are water mist, Triodide and PyroGen. The toxicity of the PyroGen and Triodide do not constitute a hazard because the suppressant is contained within an unoccupied enclosure. However, to ensure that personnel are protected from exposure, the enclosure should be vented after release to remove any traces of the suppressant or breakdown product.

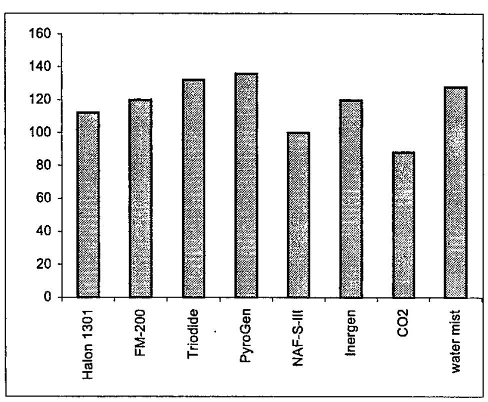

Figure 3. The cumulative citeria rating plotted for each suppressant for an Enclosed Machinery Space (fuel spray fire).

Table 14. Weighted criteria ratings for a Computer Room (electrical fire).

CRITERIA	HALON 1301	FM-200	TRIODIDE	PYROGEN	NAF-S-III	INERGEN	CO_2	WATER MIST
Ext. Conc.	0	0	0	0	0	0	0	0
Dist. Speed	24	24	24	12	24	0	0	12
Hold Time	12	12	12	12	12	12	12	12
LC_{50}	24	24	24	12	24	24	0	24
NOAEL	16	16	0	8	24	16	0	16
Post extinguishment toxicity	24	0	24	12	0	24	0	24
ODP	0	24	24	24	12	24	24	24
GWP	0	0	8	8	0	8	8	8
Environmental consequences of decomposition	8	8	8	8	8	8	8	8
Storage stability	24	16	16	24	8	16	16	16
Agent cost	4	4	0	8	4	8	8	8
Hardware cost	4	4	4	8	4	4	4	4
Hardware compatibility	8	8	8	8	8	8	8	4
Volumetric efficiency	8	4	8	8	4	0	0	8
Residue	16	16	16	0	16	16	16	0
Obscuration	0	0	0	0	0	16	0	0
System mass	4	4	4	8	4	0	0	4
Total	176	164	180	160	152	184	104	172
Ideal score	240							
% of ideal	73	68	75	67	63	77	43	72

An occupied computer room requires a non-toxic suppressant of which Inergen and water mist rate well. Triodide, which also scores well, has a cardiac sensitisation level below the design concentration.

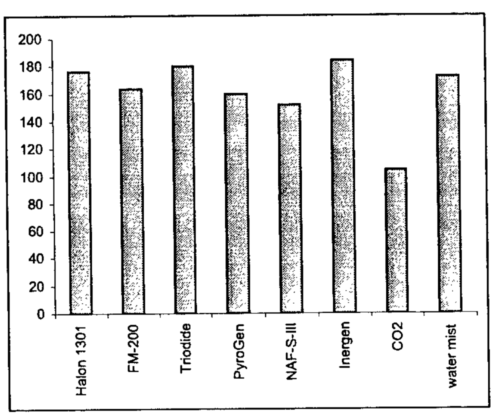

Figure 4. The cumulative citeria rating plotted for each suppressant for a Computer Room (electrical fire).

Table 15. Weighted criteria ratings for an Enclosed Computer/Electrical Cabinet (electrical fire).

CRITERIA	HALON 1301	FM-200	TRIODIDE	PYROGEN	NAF-S-III	INERGEN	CO_2	WATER MIST
Ext. Conc.	0	0	0	0	0	0	0	0
Dist. Speed	24	24	24	12	24	0	0	12
Hold Time	12	12	12	12	12	12	12	12
LC_{50}	8	8	8	4	8	8	0	8
NOAEL	8	8	0	4	8	8	0	8
Post extinguishment toxicity	8	0	8	4	0	8	0	8
ODP	0	24	24	24	12	24	24	24
GWP	0	0	8	8	0	8	8	8
Environmental consequences of decomposition	8	8	8	8	8	8	8	8
Storage stability	16	16	16	16	8	16	16	16
Agent cost	4	4	0	8	4	8	8	8
Hardware cost	4	4	4	8	4	4	8	4
Hardware compatibility	8	8	8	8	8	8	8	4
Volume efficiency	8	4	8	8	4	0	0	8
Residue	16	16	16	0	16	16	16	0
Obscuration	0	0	0	0	0	8	0	0
System mass	8	8	8	16	8	0	0	8
Total	132	144	152	140	124	136	108	136
Ideal score	200							
% of ideal	66	72	76	70	62	68	54	68

An electrical fire threat in an enclosed cabinet permits a greater number of suppressant alternatives principally because the space is unoccupied and toxicity is not a major consideration. The suppressant volume required is also not significant because of the small volume to be protected. The Halon like suppressants such as FM-200 , PyroGen and Triodide are acceptable, as their rapid distribution speed is beneficial when compared to the more slowly distributed inerting gases. The heat generated by the PyroGen system may cause further damage to electronic systems and reduce its suitability.

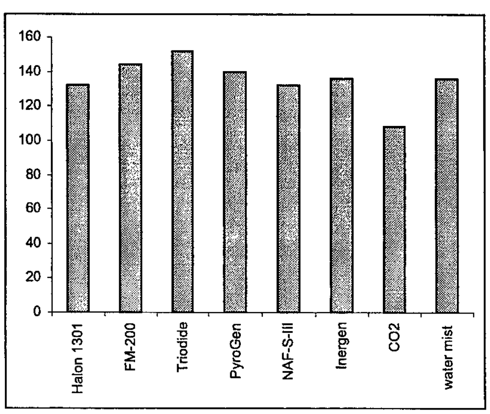

Figure 5. The cumulative criteria rating plotted for each suppressant for an Enclosed Computer/Electrical Cabinet (electrical fire).

Table 16. Weighted criteria ratings for an Aircraft Engine Bay (fuel spray fire).

CRITERIA	HALON 1301	FM-200	TRIODIDE	PYROGEN	NAF-S-III	INERGEN	CO_2	WATER MIST
Ext. Conc.	24	12	24	24	12	0	0	12
Dist. Speed	24	24	24	12	24	0	0	12
Hold Time	0	0	0	0	0	0	0	0
LC_{50}	8	8	8	4	8	8	0	8
NOAEL	8	8	0	4	8	8	0	8
Post extinguishment toxicity	0	0	0	0	0	0	0	0
ODP	0	24	24	24	12	24	24	24
GWP	0	0	8	8	0	8	8	8
Environmental consequences of decomposition	8	8	8	8	8	8	8	8
Storage stability	24	24	16	16	8	16	16	16
Agent cost	4	4	0	8	4	8	8	8
Hardware cost	4	4	4	8	4	4	4	4
Hardware compatibility.	8	8	8	8	8	8	8	4
Volume efficiency	24	12	24	24	12	0	0	24
Residue	0	0	0	0	0	0	0	0
Obscuration	0	0	0	0	0	0	0	0
System mass	12	12	12	24	12	0	0	12
Total	148	148	160	172	132	92	76	148
Ideal total	192							
% of ideal	77	77	83	90	69	48	40	77

Triodide, PyroGen and water mist score highly for aircraft engine bay applications. However, the engineering requirements necessary for water mist may not be appropriate for aircraft fitting. Aircraft engine bays pose a special problem because the suppressant will be blown out very quickly. For this application, the extinguishing concentration and the distribution speed are important criteria because of the need to discharge the smallest, but most effective amount of suppressant (lowest extinguishing concentration) in the shortest possible time. The volumetric and mass efficiencies are important considerations because of mass and volume limitations of aircraft systems, therefore FM-200, Triodide or PyroGen would be the most appropriate suppressants for this application.

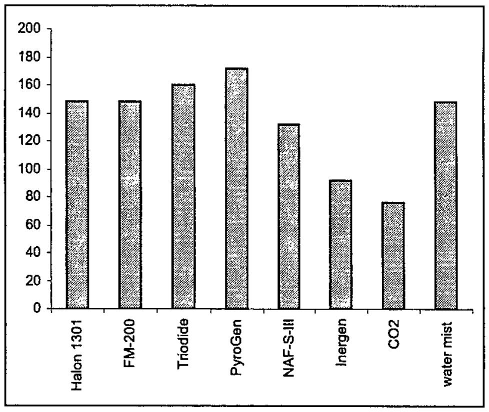

Figure 6. The cumulative citeria rating plotted for each suppressant for an Aircraft Engine Bay (fuel spray fire).

Table 17. Weighted criteria ratings for an Aircraft Cabin (Class A fire).

CRITERIA	HALON 1301	FM-200	TRIODIDE	PYROGEN	NAF-S-III	INERGEN	CO_2	WATER MIST
Ext. Conc.	0	0	0	0	0	0	0	0
Dist. Speed	24	24	24	12	24	0	0	12
Hold Time	12	12	12	12	12	12	12	12
LC_{50}	24	24	24	12	24	24	0	24
NOAEL	16	16	0	8	16	16	0	16
Post extinguishment toxicity	24	0	24	12	0	24	0	24
ODP	0	24	24	24	12	24	24	24
GWP	0	0	8	8	0	8	8	8
Environmental consequences of decomposition	8	8	8	8	8	8	8	8
Storage stability	16	16	16	16	8	16	16	16
Agent cost	4	4	0	8	4	8	8	8
Hardware cost	4	4	4	8	4	4	4	4
Hardware compatibility	8	8	8	8	8	8	8	4
Volumetric efficiency	24	12	12	24	12	0	0	24
Residue	8	8	8	0	8	8	8	0
Obscuration	0	0	0	0	0	24	0	0
System mass	12	12	12	24	12	0	0	12
Total	184	172	184	184	152	184	96	196
Ideal total	272							
% of ideal	68	63	68	68	56	68	35	72

The main threat in an aircraft cabin is a Class A (wood, paper, plastic) fire and the preferred suppressants for this type of fire are Triodide, Inergen and water mist. Triodide, although an

effective suppressant, has toxicity concerns because of its low NOAEL. For fire protection of aircraft cabins, volume efficiency limitations and engineering requirements minimise the likelihood of Inergen being used.

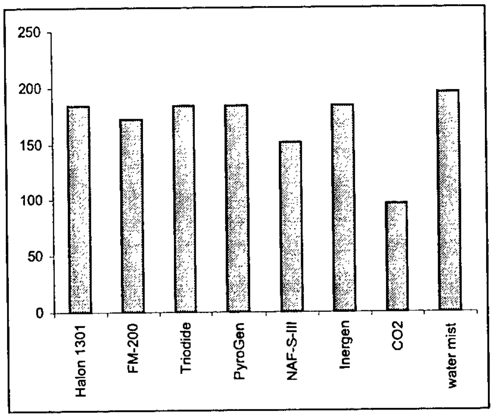

Figure 7. The cumulative criteria rating plotted for each suppressant for an Aircraft Cabin (Class A fire).

Table 18. Weighted criteria ratings for a Land Vehicle Cabin (explosion suppression).

CRITERIA	HALON 1301	FM-200	TRIODIDE	PYROGEN	NAF-S-III	INERGEN	CO_2	WATER MIST
Ext. Conc.	0	0	0	0	0	0	0	0
Dist. Speed	24	24	24	12	24	0	0	12
Hold Time	8	8	8	8	8	8	8	8
LC_{50}	24	24	24	12	24	24	0	24
NOAEL	16	16	0	8	16	16	0	16
Post extinguishment toxicity	24	0	24	12	0	24	0	0
ODP	0	24	24	24	12	24	24	24
GWP	0	0	8	8	0	8	8	8
Environmental. consequences of decomposition	8	8	8	16	8	8	8	8
Storage stability	16	16	16	8	8	16	16	16
Agent cost	4	4	0	8	4	8	8	8
Hardware cost	4	4	4	8	4	4	4	4
Hardware compatibility.	8	8	8	8	8	8	8	4
Volumetric efficiency	24	12	24	24	12	0	0	24
Residue	0	0	0	0	0	0	0	0
Obscuration	0	0	0	0	0	24	0	0
System mass	12	12	12	24	12	0	0	12
Total	172	160	184	180	140	172	84	168
Ideal total	256							
% of ideal	67	62	72	70	55	67	33	66

The principal threat to land vehicles is the detonation of ordnance that has penetrated the vehicle and Triodide, PyroGen, Inergen and water mist rate well for this application. Triodide has a rapid distribution speed, which is important for suppressing detonation, but the NOAEL is low when compared with the design concentration. Although Inergen and water mist rate well for this application, both have a relatively slow distribution speed. The volumetric efficiency of Inergen and the engineering requirement for water mist make these systems unattractive for land vehicles.

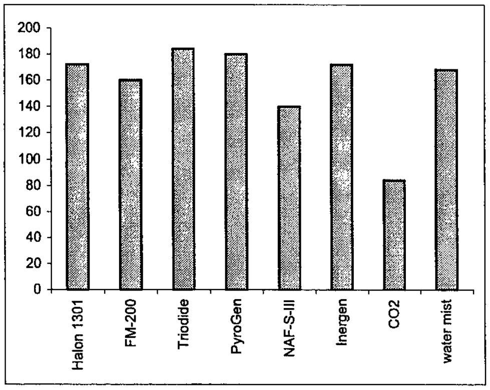

Figure 8. The cumulative criteria rating plotted for each suppressant for a Land Vehicle Cabin (explosion suppression).

7. Summary

In this paper, the properties of some of the popular fire suppressants that may be used as a Halon 1301 replacement have been examined and a risk assessment method developed to aid the selection of a suitable alternative. The method is based on rating each suppressant against a set of criteria and weighting each criterion by the importance of the criterion to the application. The selection of a fire fighting suppressant system will be primarily dependent on the application.

Each of the Halon 1301 alternatives discussed in this work are suitable for unoccupied or unmanned areas such as enclosed machinery spaces, aircraft engine bays or enclosed cabinet spaces because toxicity, either as a function of the suppressant or its breakdown products are not important criteria. FM-200, Triodide, PyroGen, NAF-S-III and CO_2 all have toxicity concerns when considered for occupied spaces

The use of Triodide is compromised by low cardiac sensitisation levels, precluding its use in occupied spaces. The NOAEL derived from epinephrine challenged dogs may over estimate human responses to Triodide exposure, however the quoted NOAEL for Triodide provides a factor of safety.

A combination of suppressant systems may be used when single systems do not provide the required fire protection outcome. One example is the protection of normally occupied marine

main machinery rooms. The high fire risks such as engine fuel lines can be compartmentalised and protected by efficient but toxic suppressants while the occupied main space can be protected by a safe total flooding system such as water mist.

The criteria selected in this work may not necessarily be the only criteria relevant for the selection of a Halon 1301 replacement, other criteria may need to be considered to fully assess the suitability of each alternative. An important feature of the method presented here is that it does not disqualify any of the alternatives where one criterion may define its unsuitability. This deficiency must be considered before attempting to use this method for selecting alternatives.

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2. TITLE	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION)
A Risk Assessment Approach for Selecting a Replacement for Halon 1301 Fire Suppressant	Document (U) Title (U) Abstract (U)
4. AUTHOR(S)	5. CORPORATE AUTHOR
Ian A. Burch, Stephen R. Kennett and Lyn Fletcher	Aeronautical and Maritime Research Laboratory 506 Lorimer St Fishermans Bend Victoria 3207 Australia

6a. DSTO NUMBER	6b. AR NUMBER	6c. TYPE OF REPORT	7. DOCUMENT DATE
DSTO-TR-1126	AR-011-817	Technical Report	March 2001

8. FILE NUMBER	9. TASK NUMBER	10. TASK SPONSOR	11. NO. OF PAGES	12. NO. OF REFERENCES
510/207/1150	98/068	DNPS (NAVSYSCOM)	34	19

13. URL on the World Wide	14. RELEASE AUTHORITY
http://www.dsto.defence.gov.au/corporate/reports/DSTO-TR-1126.pdf	Chief, Maritime Platforms Division

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

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16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CASUAL ANNOUNCEMENT Yes

18. DEFTEST DESCRIPTORS

Fire suppression, Halon, Fire extinguishing agents, Risk assessment, Halon alternatives

19. ABSTRACT

Halon 1301 has been the primary gaseous fire suppressant for total flooding applications on naval vessels since the mid 1960s. The speed and assurance of extinguishment has made it the popular choice, but other factors also contribute to its suitability as a fire suppressant. These factors include the ease of which the agent is dispersed, the minimal residue after release, its electrical non-conductivity and the minimal risk associated with short-term human exposure. Halons however, are ozone depleting substances and under the Montreal Protocol, production of these substances have been be subjected to a controlled phase-out.

A number of Halon 1301 alternatives have been assessed using a risk analysis approach. The analysis comprised identifying suppressant selection criteria and rating the suppressants against each criterion and each criterion was rated on the basis of its level of importance in different applications. Rating both suppressant behaviour and the importance of each of the criteria ensures that the end use is given due consideration in suppressant selection.

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TECHNICAL REPORT DSTO-TR-1126 AR-011-817 MARCH 2001

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